

A proposed drainage evolution model for Central Africa—Did the Congo flow east?

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Abstract

Understanding the origin of Sub-Saharan biodiversity requires knowing the history of the region's paleo-ecosystems. As water is essential for sustaining of life, the evolving geometry of river basins often have influence on local speciation. With this in mind, we analyse drainage patterns in Central and East Africa. Evidence from marine fossils suggests the Congo Basin was submerged for much of the Cretaceous, and after being uplifted drained eastwards through a paleo-Congo river towards the Indian Ocean. Two remnant peneplains in the Congo Basin are interpreted as evidence that this basin was tectonically stable on at least two occasions in the past. The lower peneplain is interpreted as the base level of the drainage pattern that had its outlet in Tanzania, at the present Rufiji Delta that was once over 500 km wide. The Luangwa, today a tributary of the Zambezi river, was a part of this drainage network. This pattern was subsequently disrupted by uplift associated with the East African Rifting in the Oligocene–Eocene (30–40 Ma). The resulting landlocked system was captured in the Miocene (5–15 Ma) by short rivers draining into the Atlantic Ocean, producing the drainage pattern of Central Africa seen today.

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1. Introduction

Africa has a unique bimodal topography inherited from its birth during the break-up of Gondwana 120–180 million years ago (Doucouré and de Wit, 2003; Stankiewicz and de Wit, 2005a,b). At that time only the southern parts of Sub-Saharan Africa stood above sea level, supporting a Gondwana-related biodiversity that included early Afrotheria mammals and a complex Gondwana-rooted flora (e.g. Murphy et al., 2001; Eizirik et al., 2001; Anderson and Anderson, 2003; Masters and de Wit, submitted for publication). Most of Africa to the north remained below sea level until the end-Cretaceous (65 million years ago). Thereafter a complex series of uplifts and stream captures created the river basins of Sub-Saharan Africa as we know

them today, and during which ex-Gondwana stocks evolved into Africa's modern biodiversity. New river-basins and related ecosystems developed across this dynamic landmass, closely entwined with the simultaneous changes in global and local climate changes during the Cenozoic. Biodiversity of Sub-Saharan Africa changed in response, including the development of grasslands and the acceleration in silicate weathering (Retallack, 2001). This is but one example of the complex way in which Earth systems interact with each other. Tracking such paleo-ecodynamics remains a formidable and urgent challenge to African Earth and life scientists, as today this biodiversity across much of Africa is being severely decimated in various ways through human over-consumption of nature's net primary production (de Wit and Anderson, 2003; Imhoff et al., 2004). Little is known about the rate of this decline, or about any biodiversity thresholds that might exist. Evolution of paleo-landscapes, and in particular of river basin and drainage patterns of Sub-Saharan Africa,

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provide a first order constraint within which to chart changes in past biodiversity, and to help predict them in future (e.g. Cotterill, 2003).

In our study we trace river basin evolution of parts of Sub-Saharan Africa from the Cretaceous, when Central Africa emerged above sea level. We show that it is possible that the proto-Congo river at first drained into the Indian Ocean, close to the present Rufiji Delta in Tanzania. We then track the changing river patterns from this hypothetical scenario to the present day.

2. Drainage pattern of contemporary Central Africa

The drainage pattern observed today in Central Africa and its surroundings is shown in Fig. 1. This figure is generated from the CIGCES Africa database (recently renamed to AEON Africa Database, de Wit and Stankiewicz, submitted for publication). This large GIS database includes all rivers and lakes in Africa, manually digitised from topographic maps. Fig. 1 does not show the database's full resolution. The average stream separa-

tion (ratio of land area to total stream length) of the database is 15 km, and this corresponds to approximately 200,000 km of digitized rivers. All streams have also been classified as either perennial or non-perennial, and all river networks ordered according to the Horton–Strahler ordering scheme (Horton, 1945; Strahler, 1957). The database also includes other parameters, such as climatic conditions over the African continent, vegetation and soil types, geology, elevation above sea level, and many others (Stankiewicz and de Wit, 2005a,b; de Wit and Stankiewicz, submitted for publication).

Central African drainage is dominated by the Congo river (Fig. 2) with its sub-circular basin. This is, however, not a classic centripetal drainage pattern one would expect from a circular depression, as there is no convergence of drainage into a central point. In the southern one-third of the basin most of the drainage is directed north. These streams show very little convergence, and mostly join west-flowing streams. The main Congo stream, and the lower reaches of Oubangui and Zaire before their confluence, flow south-west. The areas where eastwards

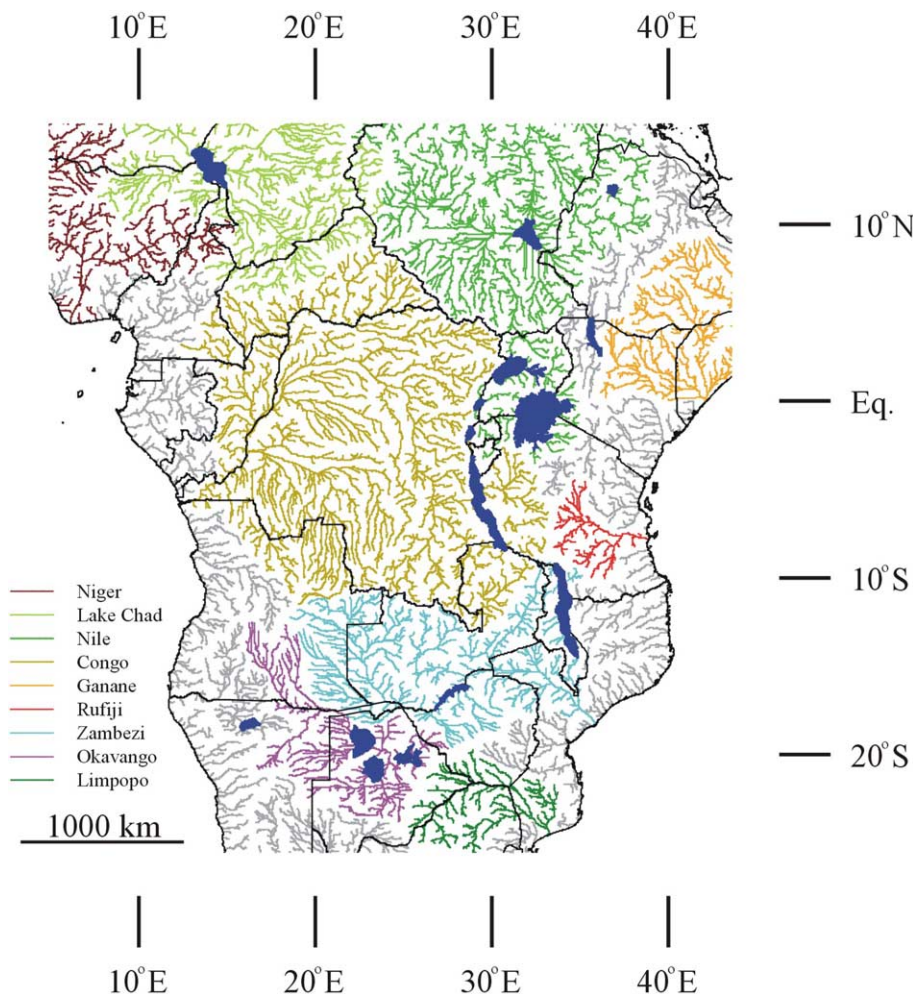


Fig. 1. Major drainage basins in Central Africa (AEON African river database based on data from De Beers Exploration). Rivers in Figs. 2a, 5 and 8b are from the same database.

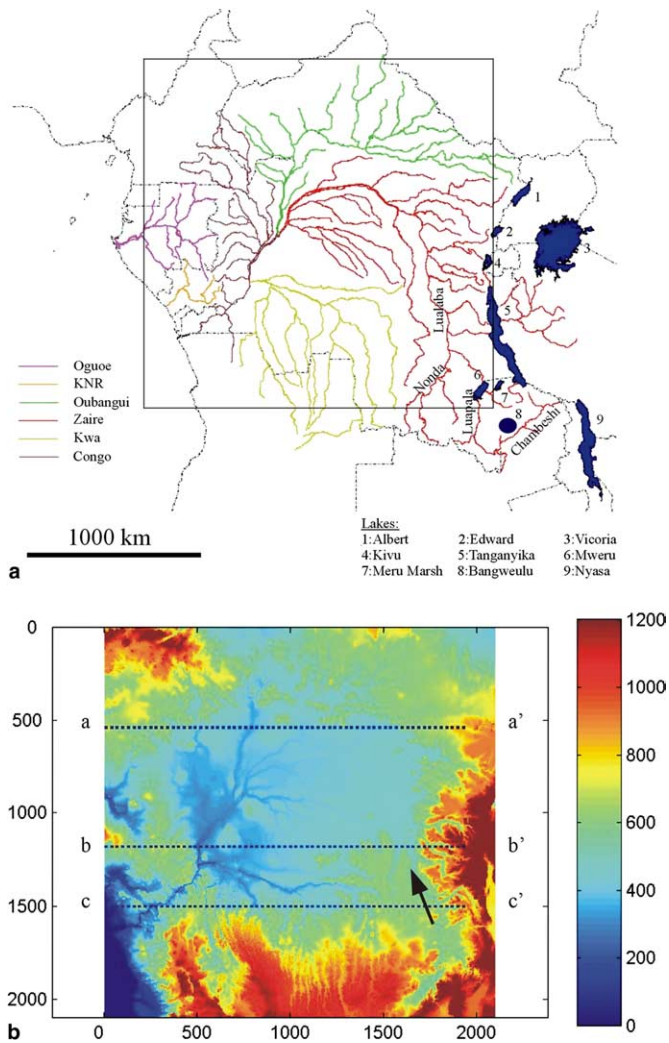


Fig. 2. (a) Main sub-basins, streams and lakes of the Congo Basin. Oguoe and KNR river systems are also shown. (b) Topography of the Congo Basin. Horizontal distance in km, vertical scale in m, truncated at 1200 m. Cross-sections in Fig. 3 are along the west–east dashed lines marked a–a', b–b' and c–c'. Black arrow shows the Lualaba valley. Digital Elevation Model from the USGS website: <http://edcdaac.usgs.gov/gtopo30>. Figs. 6 and 8a are from the same source.

and southward drainage is dominant are comparatively small. In this study the Congo refers to the river downstream from the junction of the Zaire with Oubangui (Fig. 2a).

South of the Congo Basin are the Zambezi and Okavango networks, both having general eastward drainage direction (Fig. 1). This is particularly notable for the Zambezi, as its sources are three times as far from the Indian Ocean as from the Atlantic Ocean. Even more unusual, however, is the Okavango, which after flowing for nearly 2000 km ends in an inland delta 1000 km from the Indian Ocean.

North-east of the Congo Basin, lies the Nile basin, where rivers start their 5000 km journey north. The drainage in the East African Rift valley is complicated between the Western and Eastern Rifts. A number of landlocked

sinks form small lakes, but most streams find their way into one the three Great Lakes: Victoria, Tanganyika and Nyassa. Interestingly these all drain in different directions: towards the Mediterranean Sea, the Atlantic Ocean, and the Indian Ocean, respectively. Drainage away from the East African Rift system is fairly straightforward—west into the Congo Basin, and east into the Indian Ocean.

3. Mesozoic–Cenozoic Congo Basin history

The present topography of the Congo Basin is shown in Fig. 2b. Marine fish fossils recovered from the north-east of the basin suggest the Basin was submerged below sea level throughout the Upper Jurassic and Lower Cretaceous, i.e. ~200–120 Ma (Sahagian, 1988 and references therein). The presence of similar fossils on the east coast of Africa and their absence from the west coast suggest these marine waters reached the Basin from the east in the Cretaceous (Doucouré and de Wit, 2003). The implication of this is that once the land was elevated above the sea level in the Cenozoic, the Congo network was flowing eastwards across where today the East African Rift system is found (Shackleton, 1978).

Seismic studies of the offshore Congo Fan (Uenzelmann-Neben et al., 1997; Uenzelmann-Neben, 1998) provide a history of deposition off the Atlantic coast near today's outlet of the Congo river. These studies indicate that in Late Paleogene (~55 Ma) to Late Oligocene–Early Miocene (~20–30 Ma) the only source of sediment was the Kouilou–Niari river system (KNR—Fig. 2a). In Middle-Late Miocene (~5–15 Ma) the Congo and the KNR were both active sources of sediment, and only from the Early Quaternary (~2 Ma) has the Congo been the prevailing sediment source to this delta. This is consistent with the evidence presented above that the Congo drained into the Indian Ocean prior to that time.

While it is impossible to suggest, let alone prove, the exact river pattern that drained Central Africa in the past, it would be of great interest, for example to the oil and placer diamond industries, to identify the place where a river system as large as the Congo had its outlet prior to the mid-Tertiary uplift in East Africa. To attempt this, other areas in the region must be examined in detail.

It is possible that there exists more than one of these former outlets into the Indian Ocean. If the drainage pattern could change so significantly, a drastic change could have occurred more than once. Fig. 3 shows cross-sections across the Congo Basin, on which a number of flat erosion surfaces can be seen at two distinct elevations. These are often incised by today's rivers, but remnants of these two peneplains are clear. Throughout the entire basin these plains have only two distinct elevations: 610 and 457 m above present day sea level. The 457 m plains, dissected by today's channels of the Congo network, are bounded by the 610 m plains, with an occasional inselberg rising out of the lower plain (such as the ones at ~500 and

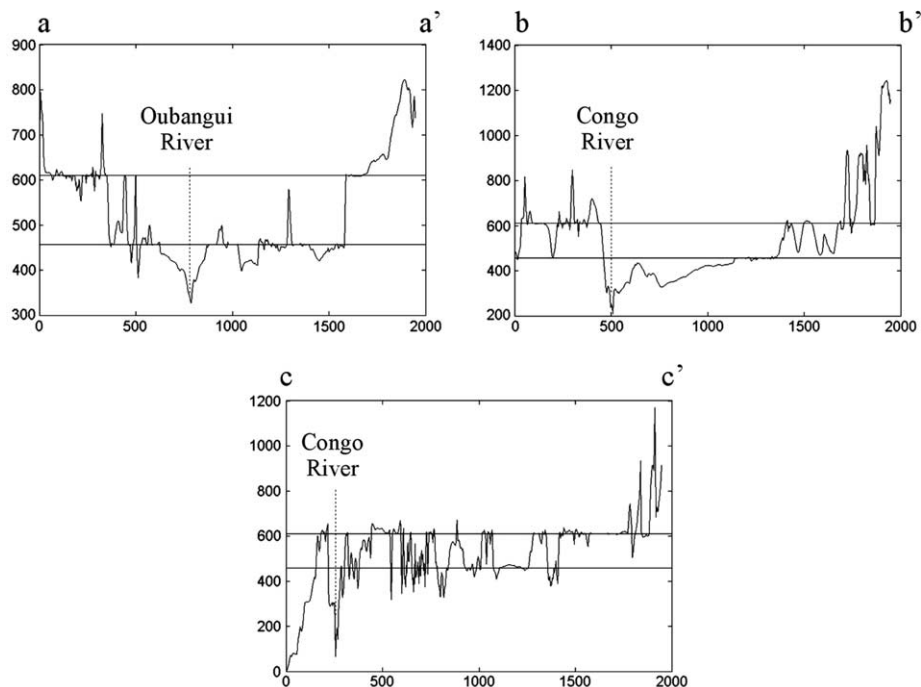


Fig. 3. West–east cross-sections through the Congo Basin (see Fig. 2b for location). Horizontal black lines mark elevations of 610 m and 457 m, to illustrate the peneplains discussed in the text.

1300 km in Fig. 3a). Because these are prone to erosion their elevations are usually just under 610 m.

In their reconstruction of Africa's paleotopography, Doucouré and de Wit (2003) computed the Late Cretaceous Congo Central Basin as a topographic low, not more than 50 m above the relatively high Cretaceous eustatic sea level, surrounded by higher ground. If this high ground is indeed a peneplain (today's 610 m plain), it corresponds to a tectonically stable period well before the Cretaceous. There is evidence from Permo-Carboniferous glacial deposits (Daly et al., 1991) for positive surface relief across Central Africa at the end of the Paleozoic (Doucouré and de Wit, 2003). Thus the higher peneplain is unlikely to be part of the Mesozoic–Cenozoic history of the basin, but instead represents a Paleozoic erosion surface. We assume that the lower (457 m) plain corresponds to the base level of the east-flowing Cretaceous paleo-Congo.

4. Southern flank of the Congo Basin: Zambezi–Okavango–Limpopo system

Some sections of the river system south of the Congo Basin (Fig. 1) have belonged to the paleo-Congo network, while parts of today's Congo have been suggested to reach the Indian Ocean at the Limpopo Delta in the Jurassic (e.g. Moore and Larkin, 2001).

A drainage evolution model has been put forward by Moore and Larkin (2001) based on a palaeo-drainage reconstruction of Thomas and Shaw (1991). The plume model of Cox (1989) shows how the Rift-related Limpopo

would have been the major river in the region following the separation of south-eastern Africa and India-Madagascar-Antarctica (East Gondwana) in the lower Jurassic, during the Karoo plume activity (~182 Ma). The drainage evolution model of Moore and Larkin (2001) suggests that in the Jurassic and Cretaceous, the Okavango, Cuando and upper Zambezi flowed south-east. Cox (1989) suggests that this south-easterly direction results from a second, younger, Parana Plume event (~130 Ma) that heralded separation of South American and Africa. However, Moore and Blenkinsop (2002) argue these rivers follow structural controls predating the plume, and that the three rivers would each join the Limpopo, as hypothesized by Moore and Larkin (2001) (Fig. 4a). The Kafue and Luangwa were major left bank tributaries of the upper Zambezi. The lower Zambezi constituted a network similar in size to today's Save.

During the early Tertiary crustal flexuring along the Okavango–Kalahari–Zimbabwe axis (OKZ—Moore, 1999; Fig. 4b) severed the links of the Okavango, Cuando and upper Zambezi with the Limpopo, and thereafter the three rivers formed a major landlocked system draining into the Kalahari Basin. Headward erosion of the Lower Zambezi in the Oligocene (initiated by the OKZ flexuring) captured the Luangwa (Fig. 4b and c). In the Lower Pleistocene continued headward erosion of the Lower Zambezi captured the Gwembe Trough, forming a link between the Upper and Lower Zambezi (Fig. 4c). At a similar time the then Upper Kafue (Chambeshi today) was captured by the Luapula tributary of the Congo. In the Upper Pleistocene captures of the Cuando and Kafue by tributaries on

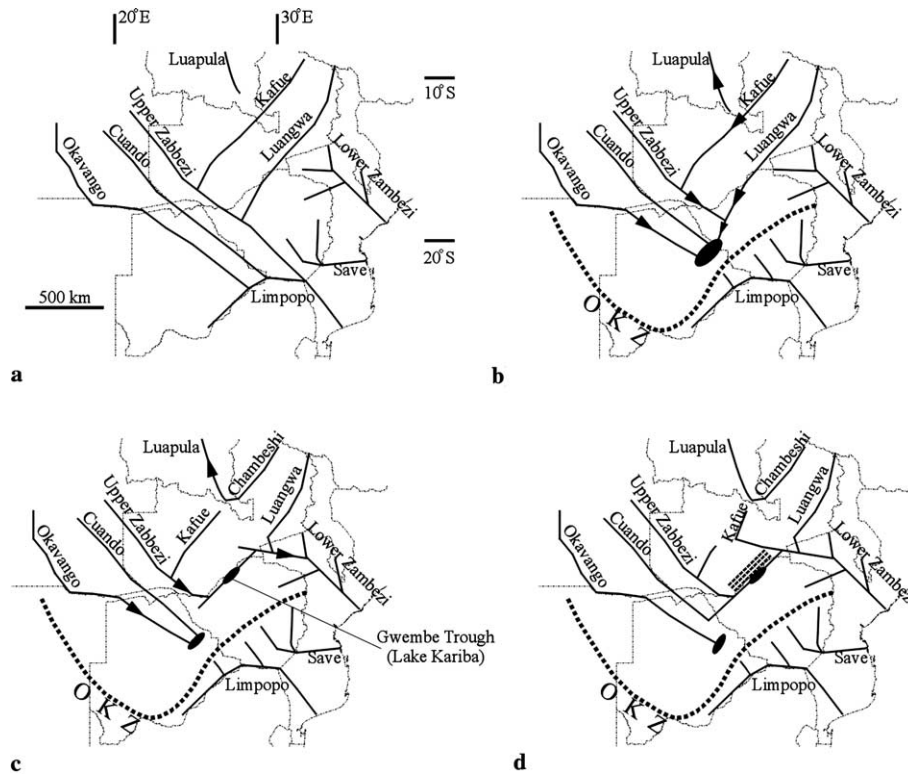


Fig. 4. Drainage evolution model of the Zambezi–Okavango–Limpopo south of the Congo Basin (modified from Moore and Larkin, 2001). Location of sections in Fig. 7 is marked as dashed bold lines in (d). (a) Cretaceous (>65 Ma), (b) Paleocene (34–65 Ma), (c) Pleistocene (~1 Ma) and (d) present.

the main Zambezi produced the pattern observed today (Fig. 4d).

5. Northern and north-western flank of the Congo Basin: West African Rifts

Irrespective of whether marine magnetic anomalies or different bathymetries were used, a tight fit between South America and Africa is difficult to achieve (e.g. Bullard et al., 1965; de Wit et al., 1988; Unternehr et al., 1988). To accommodate this, Burke and Dewey (1974) first suggested that in the Cretaceous Africa behaved like two plates separated by rifting in West Africa. A more satisfactory fit can be obtained using this concept (Reeves, 2001; Reeves et al., 2004; Reeves and Davison, 2005). A model of this Cretaceous West and Central African Rift system was presented by Fairhead (1988), and is superimposed here on the drainage of the region (Fig. 5). The rifts are dated as Mid-Upper Cretaceous between 80 and 125 Ma (Fairhead, 1988), which is around the same time, or just prior to, the Congo Basin being elevated above sea level (Sahagian, 1988; Doucouré and de Wit, 2003). The uplift associated with these structures would have produced drainage divides of the Cretaceous paleo-Congo. The Central African Shear Zone would separate it from Lake Chad (which was much larger than it is today, leading Burke (1976) to refer to it as Lake Megachad). Shoulder uplift related to the South Sudan Rift would form Congo Basin’s

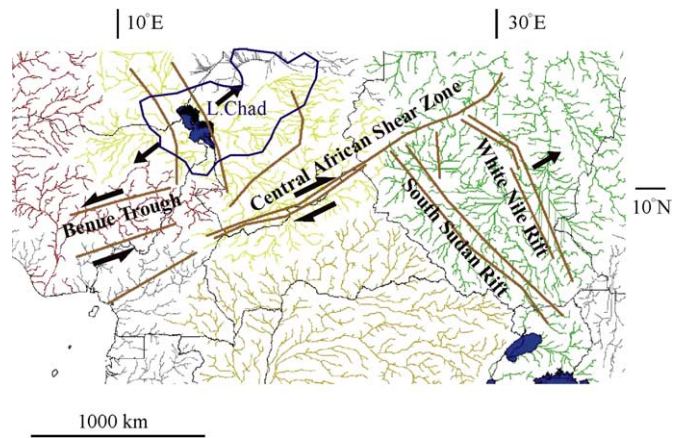


Fig. 5. Major Jurassic–Cretaceous fault systems (brown lines and black arrows) of the West and Central African Rift, after Fairhead (1988). Present drainage superimposed onto the figure, as is the possible extent of Lake Megachad after Burke (1976).

eastern watershed. The observation that the Nile, the Congo and Chad drainage basins in that area exhibit fairly simple drainage patterns away from a linear watershed that now forms the border between Sudan and the DRC, suggests this watershed has not been breached since then. Thus if the Congo drained into the Indian Ocean after the basin’s uplift above sea level, its outlet could not have been in the northern part of the basin.

6. Eastern flank of the Congo Basin: East African Rift region

The largest of the rivers draining eastwards from the East African Rift towards the Indian Ocean is the Rufiji (Figs. 1 and 6). Despite its relatively small size (drainage area of just under 200,000 km², less than half the size of Limpopo’s basin) a delta more than 500 km wide can be seen in Fig. 6a. However, today the Rufiji has a single outlet, with the outer reaches of the ‘delta’ containing outlets of separate, short (~200 km) rivers. This suggests that at some time in the past a river much larger than Rufiji today had its mouth (delta) at that spot.

Another interesting feature of the Rufiji is the prominent valley of its major southern tributary, the upper Rufiji (Fig. 6b). The valley is over 50 km wide, but it is only 150 km from its watershed. It seems reasonable to assume its headwaters were once considerably farther west from the wide valley. The northern tributary (Ruaha) is completely different—an extremely narrow gorge, flanked by high mountains on both sides. The relatively simple shape of the gorge, with one big meander, suggests the possibility of antecedent drainage, which would imply the direction of flow predates the uplift of the East African Rift valley.

7. Flow direction reversal

Flow direction reversal of major rivers is very rare, but not unheard of (e.g. Plafker, 1969; Okay and Okay, 2002).

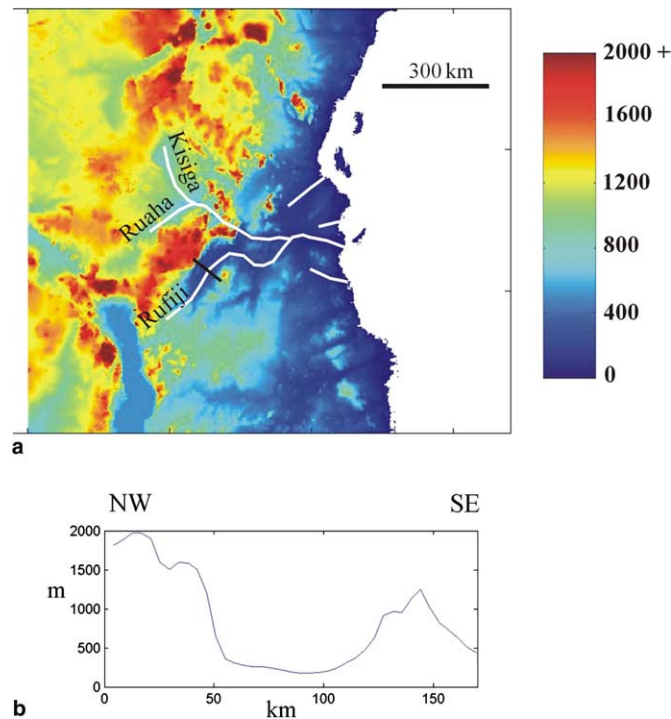


Fig. 6. (a) Topography of the Rufiji river basin and its surroundings. Solid white line shows the main streams (from north: Kisiga, Ruaha and upper Rufiji). Small streams believed to be remnants of a delta are also shown. Vertical scale in m (truncated at 2000 m). (b) Topography cross-section through the upper Rufiji gorge (marked by a black line in a).

The model of Moore and Larkin (2001), as summarized in Fig. 4, assumes flow reversal of the middle section of the Zambezi around the Gwembe Trough: the river flows in opposite directions in Fig. 4b and c. The authors attribute this reversal to headward erosion of the Lower Zambezi after its capture of the Luangwa. This is the only factor that could have caused such a reversal, as the section of the river is parallel to the OKZ flexural axis, while Oligocene–Eocene (30–40 Ma) uplift in East Africa could only stimulate southerly or south-westerly flow. If such a reversal did take place, one would expect the land on the side of the river to have a trend sloping in the opposite direction than the river today. Cross sections in Fig. 7 show this is not the case—a trend down towards north-east is clear. While this trend is not a conclusive proof (e.g. ground

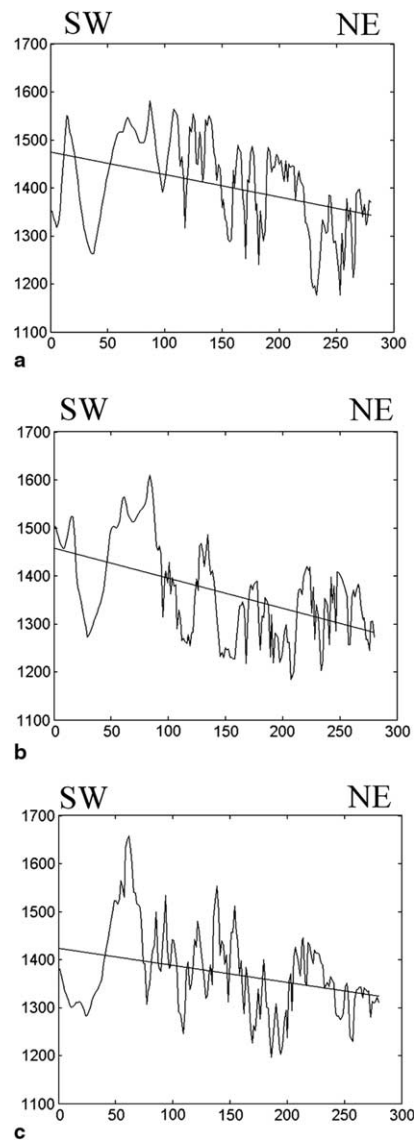


Fig. 7. Topography cross-sections parallel to the Middle Zambezi (SW-NE) on the left bank of Lake Kariba (Fig. 4). Horizontal scale in km, vertical in m. Straight lines show the general trend slope towards the north-east, the flow direction today. Distance from shore and mean slope: (a) 30 km, 0.469 m/km, (b) 50 km, 0.625 m/km, (c) 70 km, 0.351 m/km.

surface could have tilted or eroded since), it is nonetheless a point in favour of our hypothesis. The sections were taken on the north-western side (left bank) of the Middle Zambezi near the Lake Kariba, 30, 50 and 70 km from the river. The right bank was not considered, as the topography there is dominated by valleys of Zambezi's tributaries.

The alignment of Middle Zambezi and the Luangwa (Fig. 8a) does, however, strongly suggest they were indeed one river in the past. Here we propose a hypothesis that this was the case up to the Oligocene (~30 Ma), but the river flowed north-east rather than south-west. During the Oligocene uplift of East Africa, the area near today's Luangwa headwaters were uplifted sufficiently to initiate a drainage reversal. This caused the Zambezi–Luangwa system to become landlocked, until its capture by Lower Zambezi. This suggestion is supported by the fact a number of tributaries of the lower Luangwa flow in the opposite direction than Luangwa main stream, and make obtuse angles with the main river (Fig. 8b)—the same evidence

Okay and Okay (2002) provide for the reversal of the Maritsa river in Turkey.

8. Proposed model for drainage evolution since the Cretaceous

Based on the observations discussed earlier, a model for drainage evolution in Central Africa is suggested here (Fig. 9). Accepting that the Congo Basin drained to the Indian Ocean in the Late Cretaceous–Paleogene, the major trunk stream would have been located somewhere in the eastern side of the basin. The Lualaba (Fig. 2) seems the most likely candidate. It follows a deep valley, slightly to the west and roughly parallel to Lake Tanganyika. It is proposed that the Lualaba drained south, towards its junction with Nonda (which drained north-east, as it does today). From here, the combined streams then drained south-east or east, across where the East African Rift valley later developed. This river meandered to the Indian Ocean, the antecedent gorge of the Ruaha being the likely route, ending its journey at the Rufiji Delta. This hypothesis would explain the why the delta is too large to have been built up by the present day Rufiji.

Before reaching the Rufiji Delta, this Cretaceous–Paleogene river was joined by a major tributary, the Middle Zambezi–Luangwa, which was likely the same river as the upper Rufiji. The Luangwa and Rufiji valleys are aligned in the same direction (Fig. 8), and the slight displacement (~40 km) can be attributed to separation during subsequent extensional spreading in the East African Rift. The large size of the upper Rufiji valley (Fig. 6) supports the hypothesis that its headwaters were located farther west in the past. The Chambeshi (Fig. 2) also flowed north-east at that time, either joining the Luangwa, or flowing directly into the paleo-Congo.

At some stage during the uplift of East Africa, the Luangwa (except for its then lowest reaches), the flow direction of the Chambeshi, and the main trunk stream of the paleo-Congo, were reversed. The Luangwa formed a landlocked system with the Middle Zambezi until the capture by Lower Zambezi redirected it into the present site of the Zambezi Delta. The lowest parts of the Luangwa, near its confluence with the paleo-Congo, were on the eastern side of the East Africa uplift, and the drainage direction was not affected. However, the drainage area reaching this valley was significantly reduced, leaving a river in a misfit valley—the upper Rufiji seen today. The Chambeshi also had its drainage reversed and became landlocked (possibly originating Lake Bangweulu—Figs. 2 and 9). This system was captured first by the Kafue to become part of the Zambezi network, and then by the Luapula, to become part of the new Congo network. The old trunk stream of the paleo-Congo was a first-order stream draining the newly uplifted regions. Reversal of the Lualaba made the Congo a sub-continental scale landlocked basin. This is consistent with the hypothesis of Burke (1996) that such a system was captured by a small

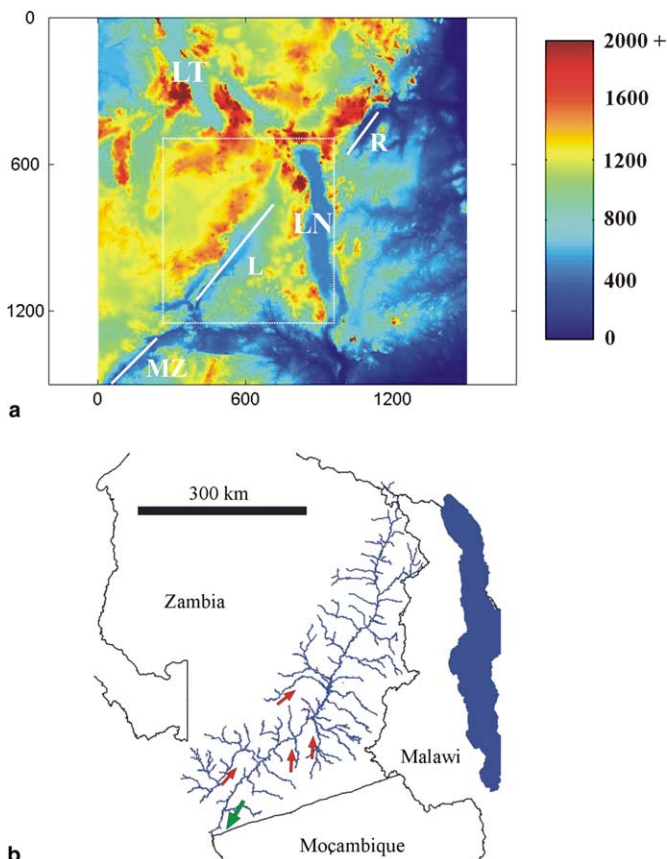


Fig. 8. (a) Topography of the area between Gwembe Trough (Lake Kariba) and Rufiji. White lines show how directions of Middle Zambezi (MZ), Luangwa (L) and upper Rufiji (R) are aligned. Horizontal distances in km, elevation in m (truncated at 2000 m). White square shows area shown in b). (b) The Luangwa tributary of the Zambezi. The green arrow marks the flow direction where the river ends by flowing into the Zambezi. A number if its tributaries in its lower reaches flow in the opposite direction (red arrows), supporting the hypothesis that the main stream once flowed north-west.

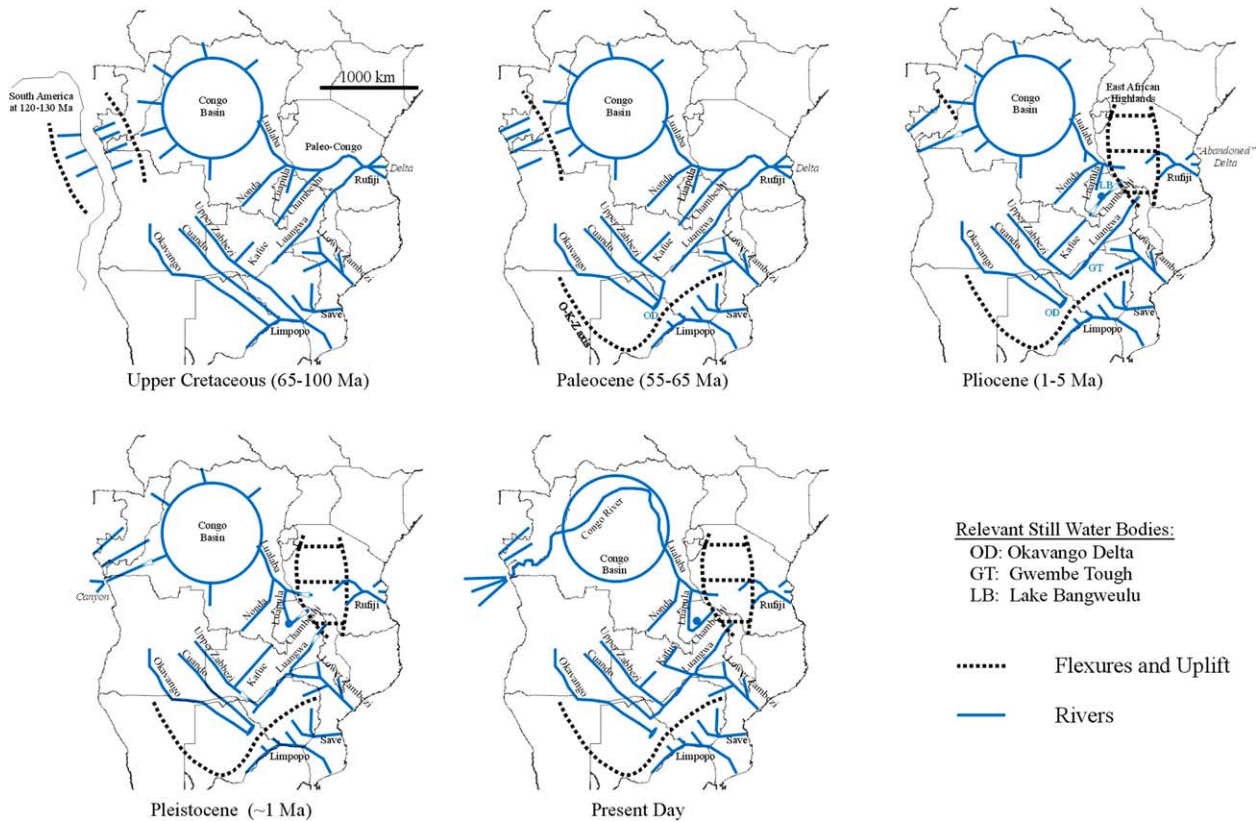


Fig. 9. Central African drainage evolution model proposed in this study, showing the drainage of a paleo-Congo river into the proto-Indian Ocean at a major Cretaceous paleo-Rufiji Delta. The subsequent drainage towards the new Atlantic coast would have had its “reflection” on the other side—the coast of South America has been included to show this in the first figure. The rift that led to the break-up of America and Africa was similar to the East African Rift which developed ~100 million years later (Reeves et al., 2004). Major rivers and lakes occurred along the Atlantic Rift until at least 120–110 Ma. In the Paleocene the proposed Late Cretaceous drainage changes due to the OKZ flexuring, “beheading” Limpopo and transforming the Okavango–Cuando–Upper Zambezi into a landlocked system. At the same time the watershed separating the Congo Basin from the rivers draining into the new Atlantic Ocean moves eastwards. During various rifting and uplift episodes in East Africa many changes take place, but by the Pliocene Rufiji is “beheaded”, and Chambeshi and Luangwa (which has earlier captured Upper Zambezi) becomes landlocked. Lualaba is also reversed due to the uplift, making the Congo Basin landlocked until the watershed to the Atlantic Ocean was breached. By the Pleistocene, the Chambeshi was captured, first by Kafue, and then by Luapula. Similarly, the Luangwa-Upper Zambezi are captured by the Lower Zambezi. Further captures of the Cuando and Kafue produce the pattern observed today.

west flowing river to produce the Congo Basin and the Congo delta on the Atlantic coast seen today.

Reeves et al. (2004) suggest that around the time of separation of Africa from South America (~110–130 Ma), the new Atlantic coastline was similar to the East African Rift system. Thus shoulder uplifts on either side of the proto-Atlantic Rift would exist, like the branches on either side of the East African Rift valley. These highlands on the African side formed the western boundary of the paleo-Congo basin. To the west of this divide relatively short rivers drained into the newly formed Atlantic Ocean. These rivers eroded into the highlands, to evolve into the Ogoe and KNR river systems. One of these Atlantic-draining river systems broke through the divide, thus capturing the Congo Basin. It is possible that more than one stream broke through the watershed and different parts of the Congo Basin drained through different outlets. This might explain the two active sources of deposition identified in seismic offshore data by Uenzelmann-Neben (1998). Such

streams would compete with each other, until the pattern seen today was produced (Fig. 9).

9. Discussion

This study presents a model for drainage evolution in Central Africa since the end of the Cretaceous. The presence of peneplains in the Congo Basin is interpreted as evidence for the basin being tectonically stable on at least two occasions in the past. The most recent one is believed to correspond to the period immediately following the retreat of the proto-Indian Ocean waters from the basin in Late Cretaceous. As the basin would be bound by shoulder uplift from the onset of Gondwana break-up to the west (~120–130 Ma), and the West-Central African Rift to the north (80–120 Ma), the most likely outlet for the drainage inside the basin was situated to the south-east of the basin into the proto-Indian Ocean. The Rufiji Delta, which appears to have once been over 500 km wide, suggests that

it was an outlet of a river much larger than the Rufiji, which today is just 800 km long. We therefore suggest the Congo drained into the Indian Ocean until the uplift of East African Highlands in the Oligocene or Eocene (30–40 Ma). The Congo then became a landlocked basin, until it was captured in the Miocene by a river system draining into the Atlantic.

A possible way to test it further would be to analyse the sediment history of the Rufiji Delta, in a way similar to the seismic studies of Uenzelmann-Neben (1998) of the Congo Delta discussed earlier. Attempts to obtain such seismic sections to be included in this study were not successful. However, informal discussions with colleagues from a well-known energy exploration company have alluded to the fact that existing seismic data has revealed a large Cretaceous delta in the Rufiji region.

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